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Black hole

Optical Gravitational Lensing Experiment



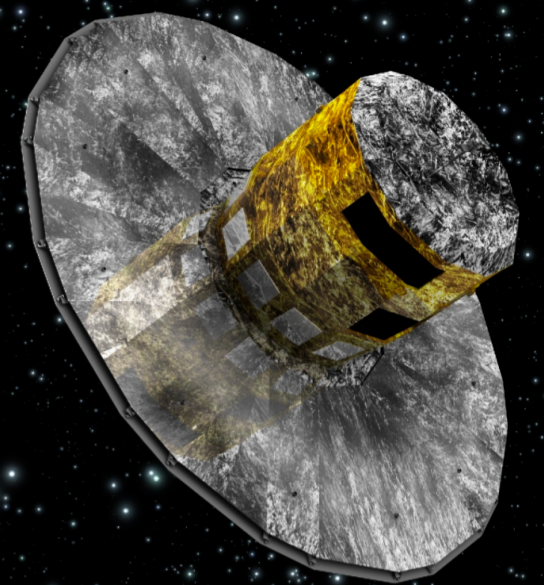
OGLE

OGLE is run by the University of Warsaw (Poland) since 1992. In 1996, it has been upgraded to use a dedicated 1.3m telescope located in the Las Campanas Observatory in Chile. The main aim of the project is to continuously monitor hundreds of millions of stars down to 21 mag towards the densest regions of the sky in order to detect gravitational microlensing events and variable stars. OGLE-III phase used 8-chip mosaic CCD with FoV of 0.34 sq.deg. in years 2001-2008. Since 2009 OGLE-IV runs with 32 CCDs and FoV of 1.4 sq.deg. In total more than 15,000 microlensing events were found by OGLE, mainly in the Galactic Bulge.

Webpage: <http://ogle.astrouw.edu.pl>

Gaia space mission

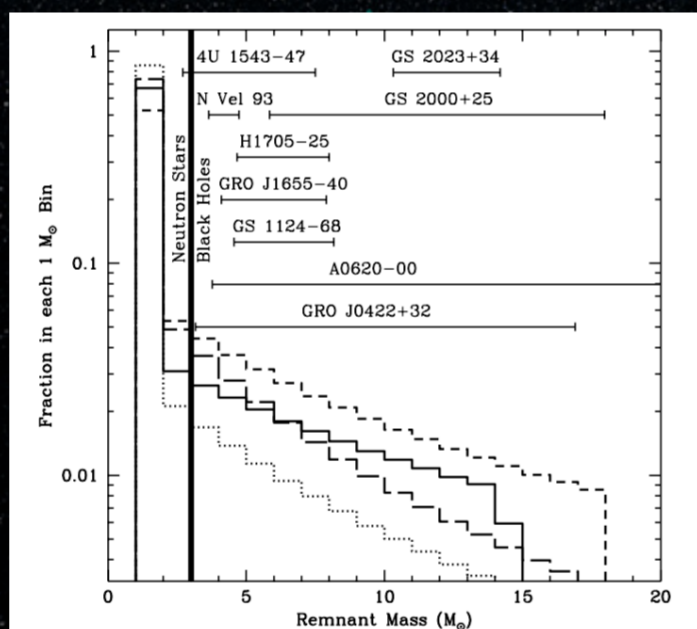
ESA's Gaia mission, launched in Dec 2013, is scanning the entire sky in order to provide at least 5 years long baseline of observations of a billion of Milky Way stars. Gaia is equipped with two 1.4m telescopes and provides astrometry and photometry down to 20 mag along with low-resolution spectra for objects classification and high-resolution spectra for radial velocities. Each object will be observed 70 times on average, but the Galactic Bulge, where majority of microlensing events occur, will be observed less frequently. This is therefore crucial to combine Gaia data with ground-based photometry from OGLE survey in order to detect single Galactic black holes.



Webpage: <http://gaia.esa.int>

Missing single black holes

Theoretical predictions (e.g., Fryer et al. 2001) suggest a continuum in mass distribution of stellar remnants. However, the observational data indicate a mass gap between masses of neutron stars and black holes. The bias in observations of X-ray binary black holes could be one of the reasons for the apparent mass gap. The ultimate solution of the missing black holes problem is to detect single stellar-mass black holes. Only microlensing is sensitive to single, non-interacting black holes in the Galaxy.



Microlensing

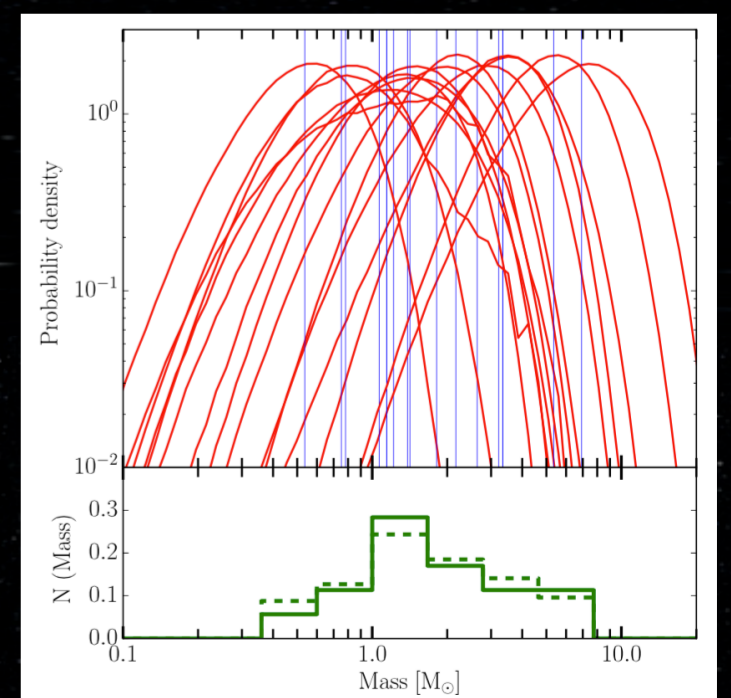
Microlensing occurs when a source, lens and the observer are aligned almost perfectly. Because sources and lenses in our Galaxy constantly change their relative positions, the observed magnification is temporal and lasts from hours to years. The motion of the Earth observer or Gaia can usually be neglected, however, in case of nearby or massive lenses the orbital motion around the Sun is significant and perturbs the observer-lens-source line-of-sight. This effect, called *microlensing parallax*, distorts the classical bell-shaped microlensing light curve (Paczynski curve).

Modelling those anomalies gives measurement of π_E , which carries information on relative distances of lens and source and helps constrain the mass of the lens, but alone is not enough to compute the mass uniquely. Superb Gaia astrometry will yield the missing measurement of the angular Einstein Ring (θ_E). $\kappa=8.144 \text{ mas}/M_\odot$.

$$M = \frac{\theta_E}{\kappa \pi_E}$$

Remnants mass function from microlensing

Among 150 million stars monitored for 8 years by OGLE-III, we identified 59 parallax events (Wyrzykowski et al., 2015) and selected 15 candidates for dark remnants. The probability distribution for mass of each event were computed using priors on the Galactic Disk and Bulge proper motions (Calamida et al. 2014) and stellar density. The observed mass distribution of lenses (see figure on the right) indicates lack of mass gap in the masses of stellar remnants. However, there still remains an ambiguity in lenses' origin and solely additional astrometric information from Gaia will allow to solve it and will yield much more accurate mass and distance measurements for future microlensing events. Gaia has been already observing microlensing events detected by OGLE-IV and those lenses will have masses measured with accuracy of $\sim 0.1 M_\odot$.



References

- Calamida et al., 2014, "First Detection of the White Dwarf Cooling Sequence of the Galactic Bulge", ApJ, 790, 164
- Fryer et al. 2001, "Theoretical Black Hole Mass Distributions", ApJ, 554, 548
- Wyrzykowski et al. 2012, "Around Gaia Alerts in 20 questions", IAUS, 285, 425
- Wyrzykowski et al. 2015, "Black Holes, Neutron Stars and White Dwarf Candidates from Microlensing with OGLE-III", arXiv:1509:044899

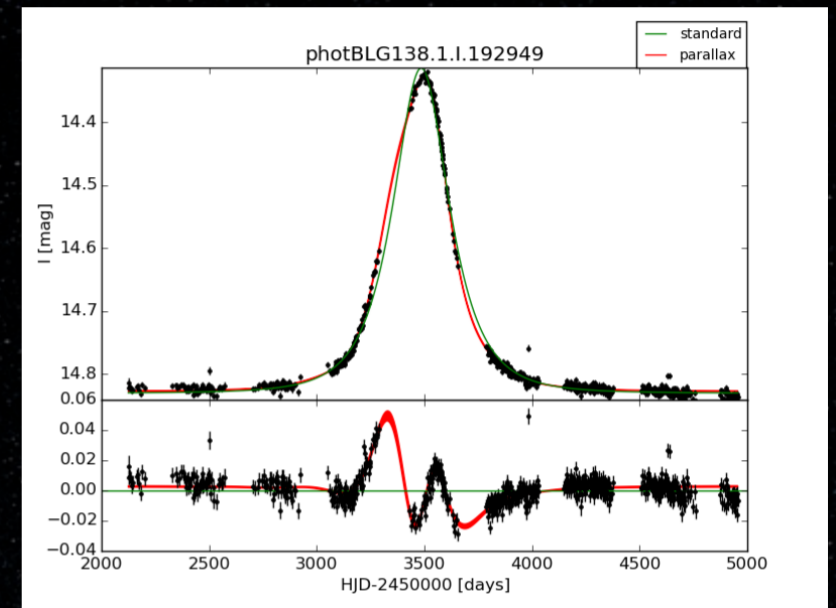
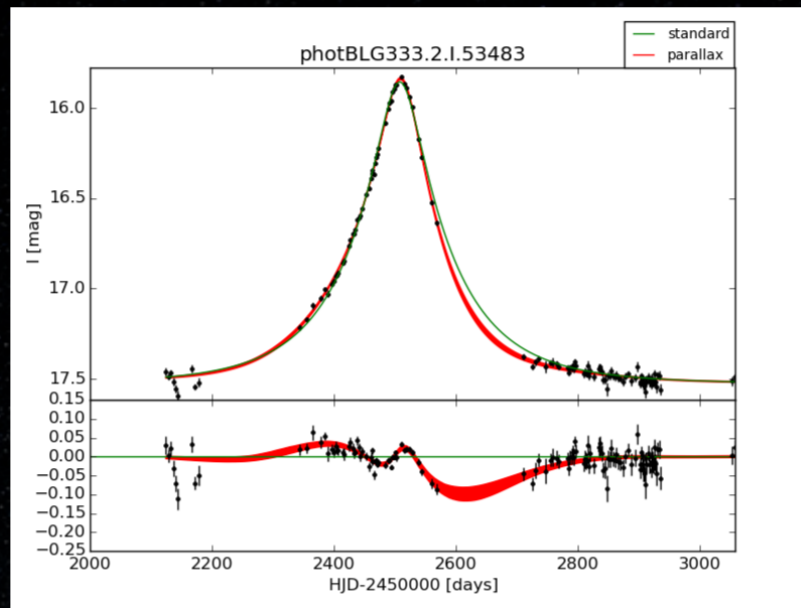
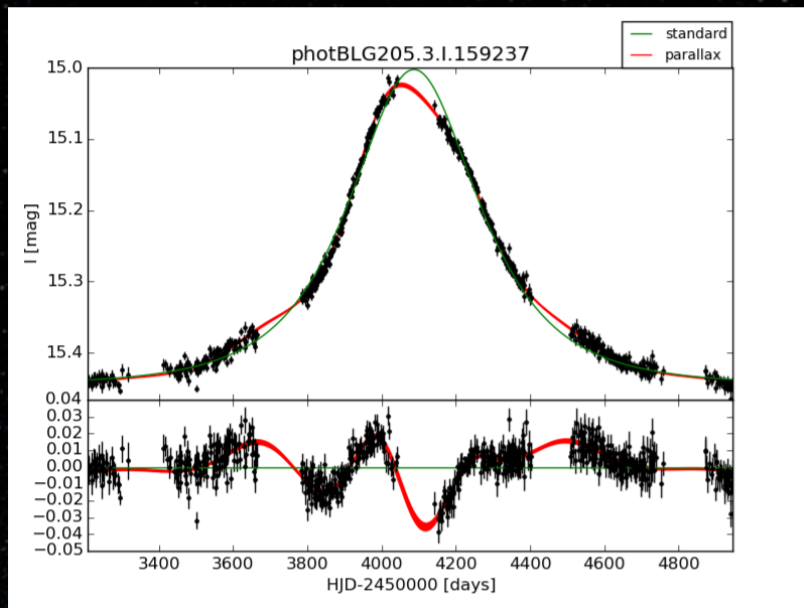
Acknowledgment

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microlenses in the Milky Way

Black hole lens candidates

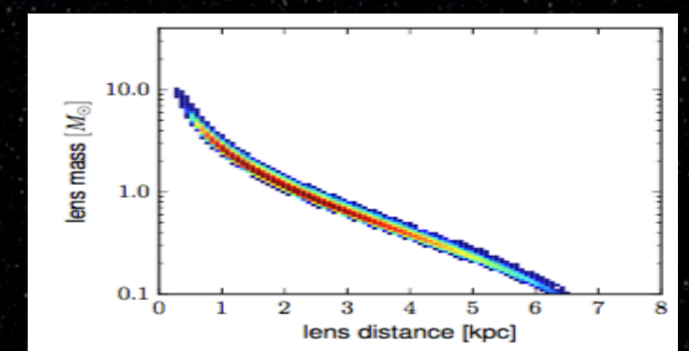
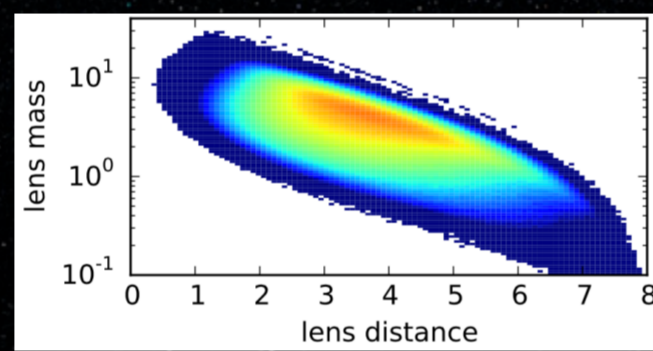
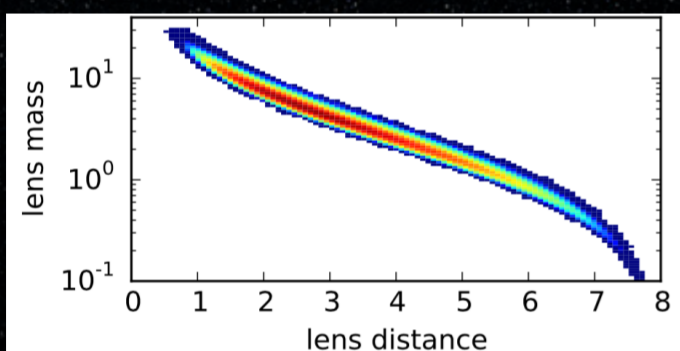
There is about 40 stellar mass black holes known – all in binary systems. Microlensing is the only technique capable of detecting single non-interacting stellar black holes. Light curves below show OGLE-III photometry centered on the peak of candidate microlensing events with a black hole lens. The duration of those microlensing events often exceeds couple of years, hence the parallax effect is clearly visible, yielding tight constraints on mass, distance and the brightness of the lensing object.



Massive and Dark

Microlensing model with parallax is not enough to uniquely compute the mass of the lens. We had to assume the distribution of lens and source proper motions as for the Disk and Bulge of the Milky Way, respectively. The plots below show distribution of most likely mass and distance for most massive lenses found among microlensing events from OGLE-III.

In a microlensing event we see the light of a distant source being amplified. It is accompanied by a constant, so called, blending light, which can be the lens itself or just another star within the seeing disk of the source. The blended light can be measured in the microlensing model as it deforms the shape of the light curve. The lens could be assumed to be a massive dark remnant if there was not enough light in the blend to accommodate the brightness of the lens with its estimated mass. The selected three events had their dark remnant probability exceeding 95%.



OGLE3-ULENS-PAR-02 (Odra)	t_E [d]	Mass [M_\odot]	Distance [kpc]
solution +	296	$6.9^{+4.0}_{-3.0}$	$1.9^{+1.2}_{-0.6}$
solution -	256	$8.3^{+4.6}_{-3.2}$	$2.4^{+1.3}_{-0.7}$

OGLE3-ULENS-PAR-13 (Obra)	t_E [d]	Mass [M_\odot]	Distance [kpc]
solution +	172	$5.3^{+2.7}_{-2.1}$	$2.9^{+1.4}_{-1.0}$
solution -	171	$4.9^{+2.8}_{-1.9}$	$2.4^{+1.4}_{-0.9}$

OGLE3-ULENS-PAR-05 (Narew)	t_E [d]	Mass [M_\odot]	Distance [kpc]
solution +	174	$3.3^{+1.9}_{-1.3}$	$2.6^{+1.3}_{-0.8}$
solution -	176	$4.0^{+2.1}_{-1.7}$	$2.0^{+1.1}_{-0.6}$

Gaia astrometry of microlensing black holes

If Gaia had operated in years 2001-2008, it would have observed those OGLE-III events, provided the sub-milliarcsecond precision astrometry for the lensed sources and allowed for a direct measurement of the Einstein ring angular size, hence the mass and distance of the lens. Figures below show simulated astrometric offsets from non-lensed positions due to microlensing centroid shift for the most probable parameters of our three black hole candidates. In all cases the deviations are of order of 1 mas, easily measurable by Gaia. Moreover, at least in case of the brighter events it would be possible also to detect the astrometric deviation in the real-time data (expected to reach <0.5 mas precision after 2016) and trigger alerts on possible black holes microlensing events (Wyrzykowski et al. 2012).

